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SPONTANEOUS AND PILOTED IGNITION OF CHEATGRASS

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ABSTRACT

Spontaneous and piloted ignition of cheatgrass (Bromus tectorum *L.*) *stems were investigated in an isothermal atmosphere. Three levels of sample moisture content were tested and minimum heat flux intensities required to produce ignition, times to ignition, and surface temperatures at time of ignition were recorded. Piloted ignition occurred at lower flux intensities and in less time than did spontaneous ignition. A significant difference in delay time to ignition was found to exist for sample moisture contents above 5.4 percent.*

OXFORD: 431.5
KEYWORDS: forest fuel ignition, ignition, pilot ignition, spontaneous ignition, cheatgrass ignition

Cheatgrass (*Bromus tectorum* L.) was introduced into North America from Europe about 1850 and rapidly spread across western rangelands until today it covers an estimated 60 million acres in the 11 western States (Hull 1965). A highly flammable fuel, cheatgrass supports an almost explosive rate of fire spread under low fuel moisture and high wind conditions (Barrows 1951; Klemmedson and Smith 1964). Many fires start in cheatgrass and burn thousands of acres of rangeland each year.

Ignition temperatures of fuels, such as cheatgrass, must be known if fire spread models (Rothermel 1972) and ignitibility criteria (Anderson 1970) are to be used to appraise fire potential of forest and range fuels. This information is also needed for use in fire prevention, hazard control, and in law enforcement when establishing responsibility for fire starts. The advent of the catalytic converter and the higher exhaust temperatures of the newer model automobiles make the need for this information even more pressing. A study of ignition properties of fine forest fuels at the Northern Forest Fire Laboratory included cheatgrass as one of the fuels to be examined. The results of this portion of the study are reported in this paper. Results of similar studies on pine needles have been previously reported (Stockstad 1975).

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OBJECTIVES AND PROCEDURES

The objectives of this study were to determine (1) the time required for ignition to occur, (2) the surface temperature at the onset of ignition, and (3) the effect of fuel moisture content and initial heat source intensity on (1) and (2). The Stockstad-Lory ignition furnace (Stockstad and Lory 1970; Stockstad 1972, 1973) was used for all testing. Both spontaneous and piloted ignition were studied using a 2.54-cm (1-inch) by 0.14-cm (0.055-inch) section of cured cheatgrass stem section.

Cheatgrass stem sections were passed through a 0.14-cm (0.055-inch) "go-no-go" gage to obtain samples of uniform diameter. Uniform sample length was obtained by cutting sections from stems of desired diameter with a miniature circular saw driven by a modified high-speed hand tool. All samples were kept at ambient air temperature of 22° to 24° C prior to testing.

Temperature of the cheatgrass sample was measured by a 3-mil platinum versus platinum 10-percent rhodium thermocouple placed on the forward end of the sample. The ignition chamber temperature was measured by a similar thermocouple approximately 3 mm from the sample thermocouple (Stockstad 1972). Both thermocouples were connected to a recorder and their output plotted against time.

Stem sections of cheatgrass were placed in conditioning cabinets containing saturated salt solutions (Schuette 1965) to provide three moisture levels (5.4, 10.1, and 18.6 percent). Spontaneous and piloted ignition tests were replicated 20 times for each moisture level and furnace temperature. Moisture content was determined on an ovendry weight basis by using both the conventional ovendry method and the vacuum ovendry method.

The minimum furnace temperature used for each moisture content in the testing program was that at which no ignitions were observed in 20 trials. Furnace temperature was then raised 10° C and another series of 20 tests observed. This procedure was repeated until a furnace temperature was reached at which 100 percent of the samples ignited.

Three points on the thermocouple traces from a spontaneous ignition test were considered in the analysis (fig. 1):

1. The point at which the sample temperature trace crossed and exceeded the ignition chamber trace was considered to be the beginning of the exothermic reaction.

2. The second significant change in the sample trace was the point where the exothermic reaction increased in intensity, resulting in an abrupt rise in the temperature of the sample. This point was considered to be the time and temperature at which the spontaneous ignition process would continue to the end result--visible glowing.

3. An event marker activated by the test operator indicated the time and temperature at which visible glowing was observed. Tests indicated that operator reaction time was one-half second; so this correction was subsequently applied to determine actual glowing ignition time and temperatures.

Pilot ignition tests were conducted in the same manner as spontaneous ignition tests, except for the introduction of a pilot flame (Stockstad 1972). Pilot ignition usually occurred at temperatures below actual furnace temperature; therefore, the beginning of the exothermic reaction, if one occurred, could not be determined by the previously described criteria. The point at which flaming ignition took place was marked by an abrupt, nearly vertical rise in the trace. For this reason, an operator-activated event marker was not necessary for the pilot ignition testing.

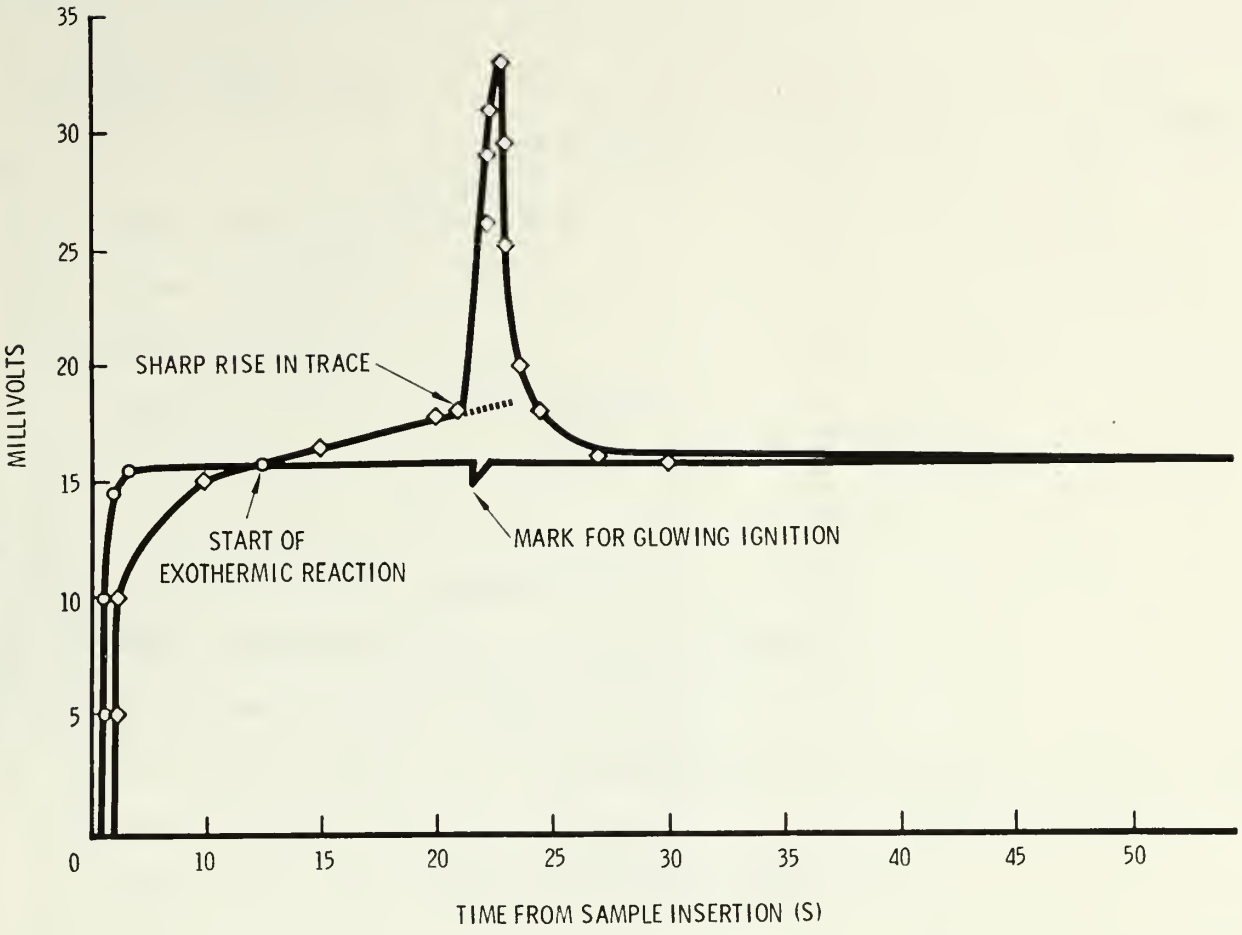

Figure 1.--Sample (◇) and ignition chamber (O) thermocouple traces from a spontaneous ignition test of a 2.54- by 0.14-cm section of cured cheatgrass stem.

PREDICTION OF HEATING RATES

Calculations were made to determine the heat transfer coefficients existing in the furnace during heating of the cheatgrass stem sections. Heating curves were calculated for a furnace temperature of 460° C. Values from this curve were later used to determine the total heat flux necessary to produce ignition. The assumption was made that the cheatgrass stem section would possess properties similar to those of a cylinder in parallel flow. Based on this assumption, the chart plotted by Heisler (1947) was used to obtain values for the Fourier number needed in the calculations.

Formulas used in the calculations were:

$$\theta = \frac{t_o - t_f}{t_i - t_f} = \text{a dimensionless temperature ratio} \qquad (1)$$

$$N_{Fo} = \frac{\alpha\tau}{r_1^2} = \text{Fourier number} \qquad (2)$$

(con. next page)

$$1/N_{Bi} = \frac{K}{hr_1} = \text{Biot number} \qquad (3)$$

where

t_o = sample temperature, °F at time t

t_f = furnace temperature, °F

t_i = ambient temperature, °F

τ = time from insertion of sample, seconds

$h = h_r + h_c$ = total heat flux for furnace at any given temperature, cal/cm^2 - °C.

where

h_r = radiant flux and h_c = convective flux

r_1 = radius of cheatgrass stem = 0.071 cm (0.028 inch)

K = thermal conductivity of cheatgrass stem

= 2.35×10^{-4} cal/cm^3 - sec, °C (Byram 1952)

α = thermal diffusivity of cheatgrass stem

= 1.059×10^{-3} cm^2/sec, which was calculated from:

$$\alpha = \frac{K}{\rho C_p}$$

where

ρ = 0.66 gm/cm^3 (Brown 1970)

C_p = 0.19 cal/gm (Byram 1952).

Assuming various sample temperatures between 38° and 454° C and furnace temperatures of 460° C, τ was calculated and resulting values were tabulated in appendix table 1. These values are also plotted in figure 2, together with the curve resulting from the actual heating of a cheatgrass stem section.

The actual heating rate was faster than the calculated rate. A possible explanation could be the increase in adsorption of radiant heat flux by the sample as it darkened during the heating process. The heating of organic substances undergoing thermal decomposition is not a simple thermodynamic process; consequently, the use of a single Fourier number may not be applicable as it is for a metal cylinder. It seems likely that minor exothermic processes might begin relatively early as the sample is being heated, thereby contributing to a temperature rise more rapid than would be expected for inorganic materials. The use of a single value for the heat transfer coefficient existing at a given furnace temperature would also account for some of the disparities between the curves.

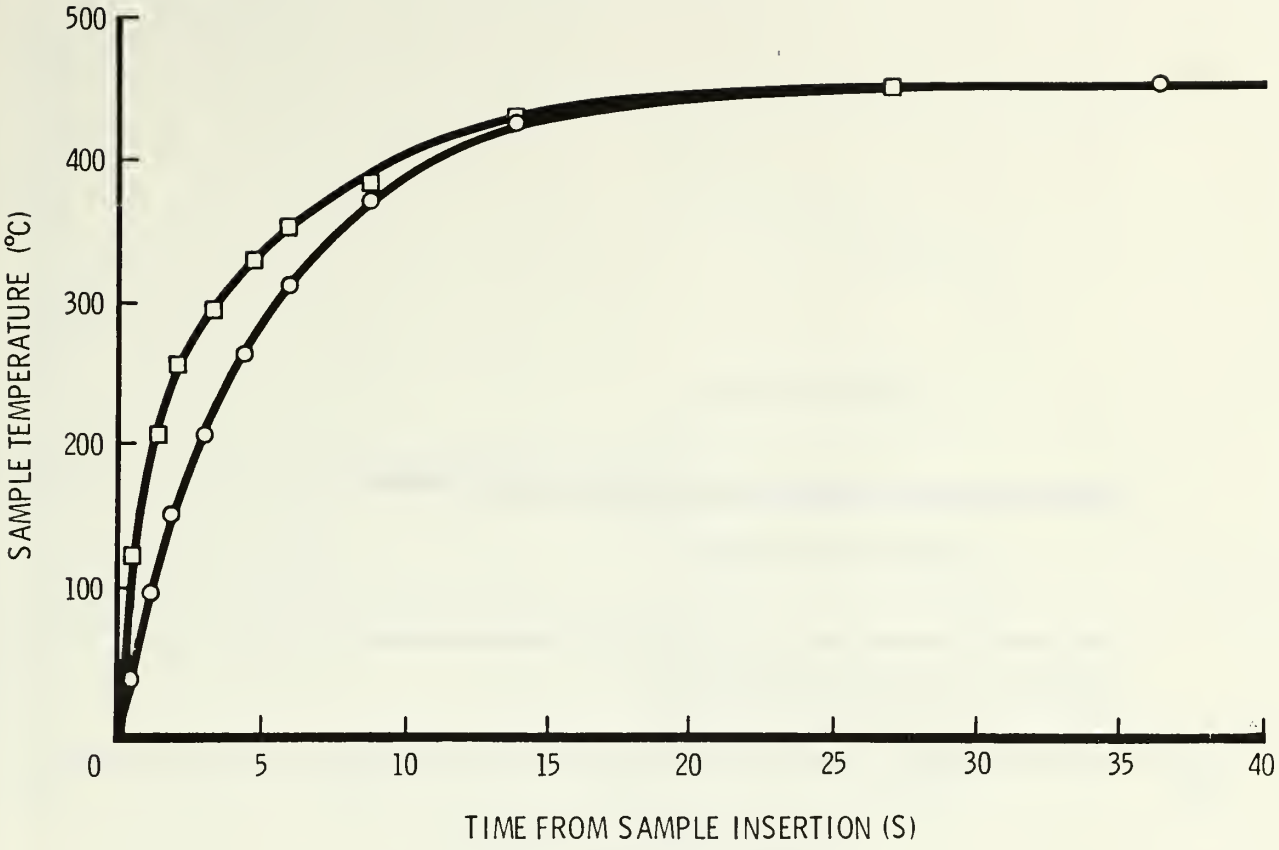

Figure 2.--Calculated (O) and actual (□) time-temperature history of a 2.54- by 0.14-cm section of cheatgrass stem at a moisture content of 5.4 percent during spontaneous ignition at a furnace temperature of 460° C.

RESULTS

The results of the 180 spontaneous ignition tests and the 180 pilot ignition tests are given in appendix tables 2 through 7.

The minimum furnace temperature at which spontaneous ignition occurred was 450° C. A furnace temperature of 460° C was needed to produce spontaneous ignition at all moisture contents tested. A furnace temperature increase from 450° to 460° C increased the probability of ignition from approximately 50 percent to 100 percent.

Figure 3 shows the relationship between the time required for the ignition processes to occur and the moisture contents tested at 460° C, the temperature at which 100 percent ignitions were first obtained.

Analysis of variance at the 95 percent level of confidence did not show a significant difference in the times to glowing ignition or the temperature of ignition for the fuel moisture contents and furnace temperatures examined.

The minimum furnace temperatures at which pilot ignition occurred was 380° C. A furnace temperature of 390° C was needed to produce pilot ignition at all moisture contents tested. As was the case for spontaneous ignition, a 10° C increase in furnace temperature increased the percentage of ignitions from approximately 50 percent to 100 percent.

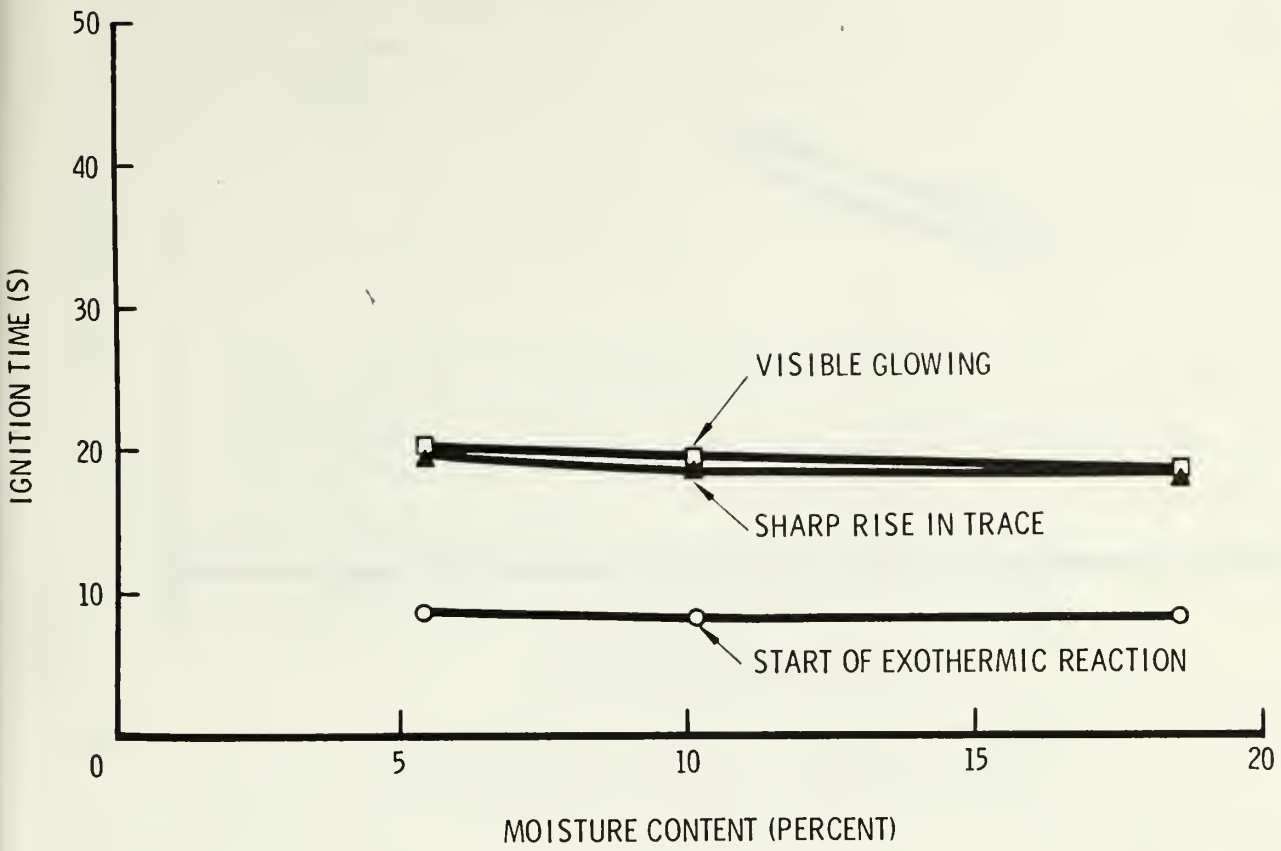

Figure 3.--Ignition time versus moisture content for spontaneous ignition of cheatgrass stem sections at a furnace temperature of 460° C.

The average times required for ignition to occur at various furnace temperatures for the three fuel moisture contents tested are plotted in figure 4. Figure 5 shows the relationship between the time required for ignition to occur and the various moisture contents tested at 390° C, the temperature at which 100 percent ignition occurred. Analysis of variance at the 95 percent level of confidence indicated a significant difference in time to ignition for all fuel moistures and furnace temperatures examined. Further analysis using Tukey's test showed a significant difference in time to ignition between all moisture contents tested.

Analysis of variance at the 95 percent level of confidence did not show a significant difference in the ignition temperatures obtained.

Spontaneous ignition occurred at a minimum flux intensity of 0.75 cal/cm^2-s, although 0.79 cal/cm^2-s was necessary before ignition took place at all moisture contents tested. Pilot ignition occurred at a minimum flux intensity of 0.56 cal/cm^2-s; 100 percent of all samples tested ignited at intensities of 0.57 cal/cm^2-s.

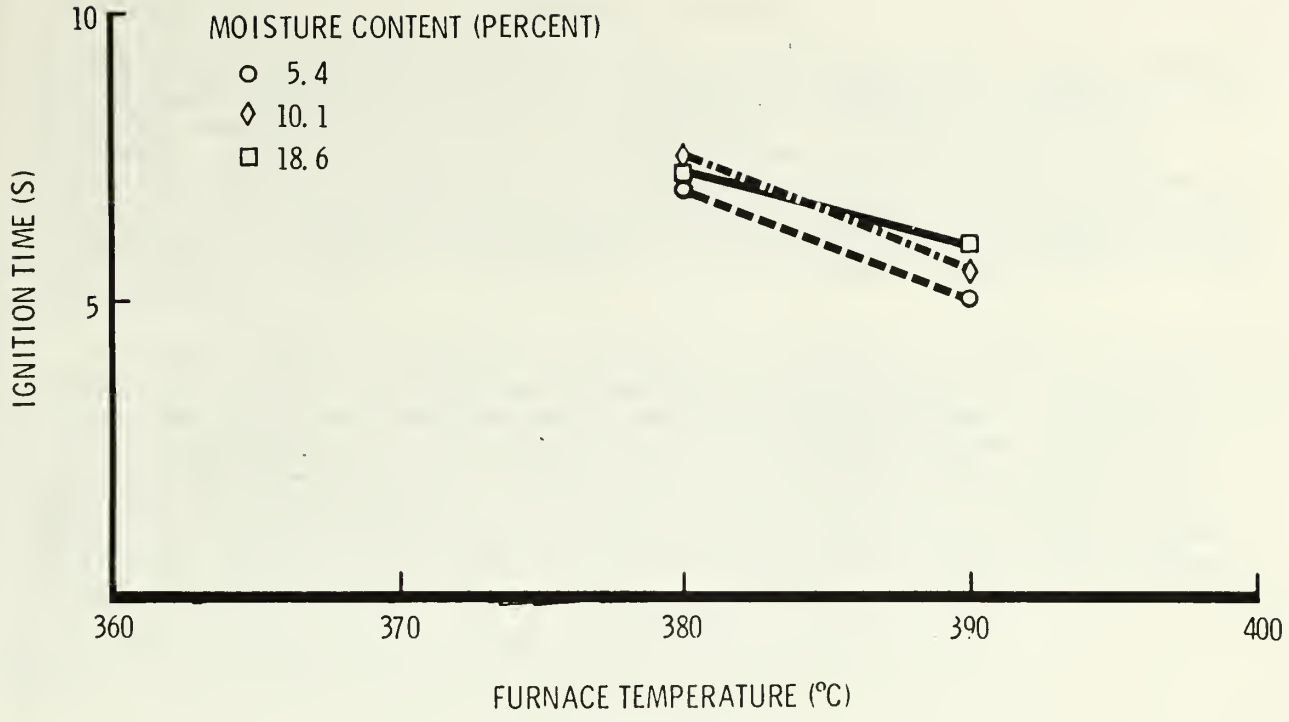

Figure 4.--Ignition time versus furnace temperature for pilot ignition of cheatgrass stem sections for various moisture contents.

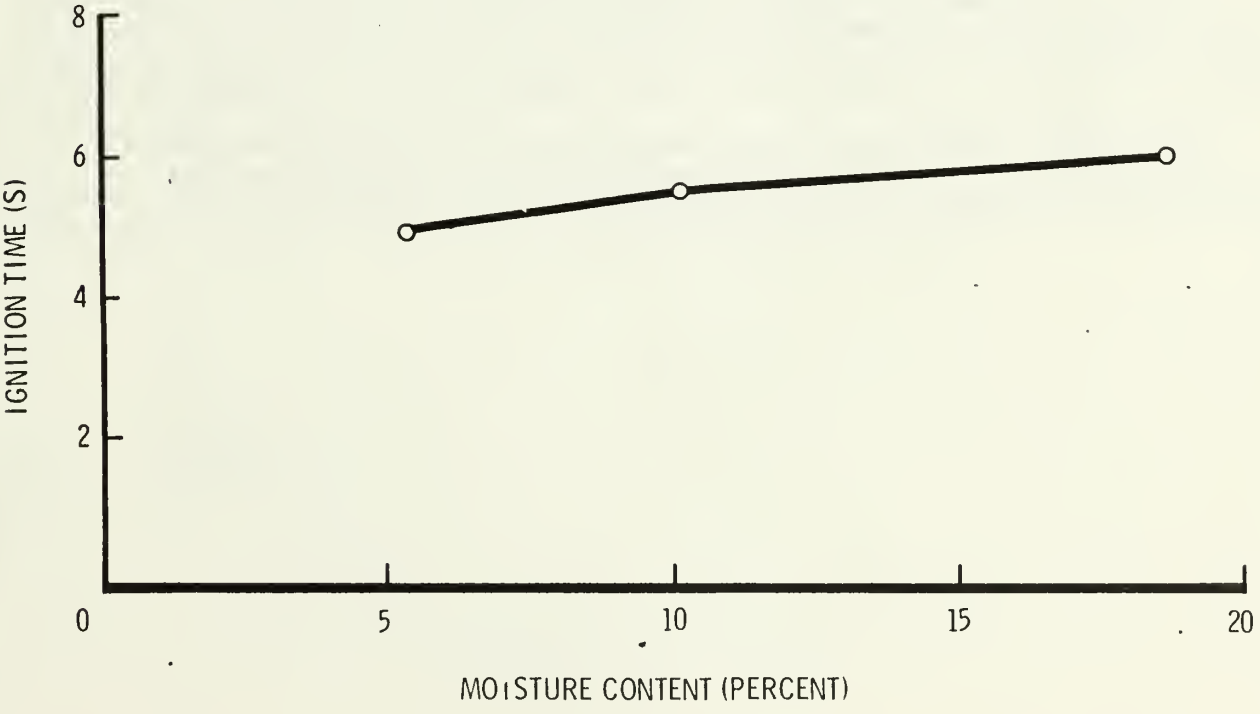

Figure 5.--Ignition time versus moisture content for pilot ignition of cheatgrass stem sections at a furnace temperature of 390° C.

DISCUSSION OF RESULTS

The total heat transfer coefficient for furnace temperatures of 450° and 460° C for each sample moisture content was calculated and is tabulated in appendix table 8. The average temperature for each 20 tests at which the exothermic reaction was considered to begin is also listed. From these values, an average heat transfer coefficient and exothermic temperature were determined. The total heat flux needed to produce spontaneous ignition at all moisture contents tested was then calculated to be 5.8 cal/cm^2 or a total of 18.6 calories. By using this value, an average ignition delay time of 9.5 seconds was calculated. The actual average ignition delay time was also 9.5 seconds.

If a pilot flame is present, the total heat flux necessary to produce ignition is altered considerably. The total heat transfer coefficient for furnace temperatures of 380° and 390° C for each sample moisture content was calculated and is listed in appendix table 9. Also listed in this table is the average temperature for each 20 tests at which flaming ignition occurred. The average heat transfer and ignition temperature were then determined. The total heat flux necessary to produce flaming ignition was calculated to be 2.7 cal/cm^2, or a total of 7.8 calories. The average ignition delay time was calculated to be 6.3 seconds, compared to an actual average ignition delay time of 6.2 seconds.

CONCLUSIONS

Based on the results, certain general conclusions can be drawn concerning ignition of cheatgrass stem sections when heated to ignition in an isothermal atmosphere. In the absence of a pilot flame, spontaneous ignition will occur at moisture contents up to at least 18.6 percent if the igniting agent is capable of producing a heat flux intensity of 0.79 cal/cm^2-s for 9.5 seconds. In the presence of a pilot flame, ignition will occur at moisture contents up to at least 18.6 percent if the igniting agent is capable of producing a heat flux intensity of 0.57 cal/cm^2-s for a period of 6.3 seconds.

A significant difference at the 95 percent level of confidence in delay time to ignition was shown to exist for pilot ignition for cheatgrass stem section moisture contents above 5.4 percent. From this, we conclude that the probability of an ignition occurring decreases as the moisture content rises above 5.4 percent.

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APPENDIX

Table 1.--*Calculated and actual time for a cheatgrass stem section to reach a given temperature at a furnace temperature of 460° C*

Stem section temperature (°C)	460° C furnace temperature	
	Calculated time	Actual time
	Seconds	
38	0.5	0.2
93	1.4	.4
149	1.9	.6
204	3.2	1.5
260	4.6	2.4
316	6.0	4.3
371	8.8	7.3
427	13.8	13.5
454	36.4	27.0

Table 2.--*Percentage of spontaneous ignitions of cheatgrass stem sections at selected furnace temperatures for 20 tests per moisture content*

Furnace temperature (°C)	Percent moisture content		
	5.4	10.1	18.6
440	0	0	0
450	50	60	55
460	100	100	100

Table 3.--*Time to spontaneous ignition of cheatgrass stem sections at selected furnace temperatures averaged for 20 tests per moisture content*

Furnace temperature (°C)	Start of exothermic reaction			Sharp rise in trace			Visual glowing		
	Percent moisture content			Percent moisture content			Percent moisture content		
	5.4	10.1	18.6	5.4	10.1	18.6	5.4	10.1	18.6
	Seconds								
440	--[1]	--	--	--	--	--	--	--	
450	11.6	10.0	10.1	31.4	23.6	40.3	31.4	23.6	40.3
460	8.7	8.3	8.3	19.8	18.5	18.4	20.0	19.4	18.7

[1] Dashed lines indicate no ignition occurred.

Table 4.--*Temperatures at time of spontaneous ignition of cheatgrass stem sections averaged for 20 tests per furnace temperature and varying moisture contents*

Furnace temperature (°C)	Start of exothermic reaction			Sharp rise in trace			Visual glowing		
	Percent moisture content			Percent moisture content			Percent moisture content		
	5.4	10.1	18.6	5.4	10.1	18.6	5.4	10.1	18.6
	°C								
440	--[1]	--	--	--	--	--	--	--	--
450	403	389	382	406	405	409	406	406	411
460	398	392	395	421	414	420	424	419	422

[1] Dashed lines indicate no ignition occurred.

Table 5.--*Percentage of pilot ignitions of cheatgrass stem sections for selected furnace temperatures averaged for 20 tests per moisture content*

Furnace temperature (°C)	Percent moisture contents		
	5.4	10.1	18.6
370	0	0	0
380	55	65	60
390	100	100	100

Table 6.--*Time to pilot ignition of cheatgrass stem sections for selected furnace temperatures averaged for 20 tests per moisture content*

Furnace temperature (°C)	Percent moisture contents		
	5.4	10.1	18.6
	Seconds		
370	--[1]	--	--
380	6.9	7.2	7.2
390	4.9	5.4	6.0

[1] Dashed lines indicate no ignition occurred.

Table 7.--*Temperatures at time of pilot ignition of cheatgrass stem sections at selected furnace temperatures averaged for 20 tests per moisture content*

Furnace temperature (°C)	Percent moisture contents		
	5.4	10.1	18.6
	°C		
370	--[1]	--	--
380	317	316	321
390	322	319	326

[1] Dashed lines indicate no ignition occurred.

Table 8.--*Average heat transfer coefficient (h) and temperature at initiation of exothermic reaction during spontaneous ignition of cheatgrass stem sections for 20 tests per moisture content at selected furnace temperatures*

Furnace temperature (°C)	Sample moisture content	h	Start of exothermic reaction
	Percent	*Cal/cm²-°C*	*°C*
450	5.4	0.019	403
	10.1	.017	389
	18.6	.017	382
460	5.4	.015	398
	10.1	.014	392
	18.6	.014	395
Average of all tests:		.016	393

Table 9.--*Average heat transfer coefficient (h) and temperature at flaming ignition during pilot ignition of cheatgrass stem sections for 20 tests per moisture content at selected temperatures*

Furnace temperature (°C)	Sample moisture content	h	Flaming ignition
	Percent	*Cal/cm²-°C*	*°C*
380	5.4	0.010	317
	10.1	.010	316
	18.6	.010	321
390	5.4	.007	322
	10.1	.009	319
	18.6	.009	326
Average of all tests:		.009	320

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